GaN-based High Temperature and Radiation-Hard Electronics for Harsh Environments

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ABSTRACT

We develop novel GaN-based high temperature and radiation-hard electronics to realize data acquisition electronics and transmitters suitable for operations in harsh planetary environments. In this paper, we discuss our research on AlGaN/*GaN metal-oxide-semiconductor (MOS) transistors* that are targeted for 500 ºC operation and >2 Mrad radiation hardness. For the target device performance, we develop Schottky-free AlGaN/GaN MOS transistors, where a gate electrode is processed in a MOS layout using an Al_2O_3 gate dielectric layer. The AlGaN/GaN MOS transistors fabricated with the wide-bandgap gate oxide layer enable Schottky-free gate electrodes, resulting in a much reduced gate leakage current and an improved sub-threshold current than the current AlGaN/GaN field effect transistors. In this study, characterization of our AlGaN/GaN MOS transistors is carried out over the temperature range of 25°C to 500°C. The I_{ds}-V_{gs} and I_{ds}-V_{ds} curves measured as a function of temperature show an excellent pinch-off behavior up to 450°C. Off-state degradation is not observed up to 400 °C, but it becomes measurable at 450 °C. The off-state current is increased at 500 °C due to the gate leakage current, and the AlGaN/GaN MOS HEMT does not get pinched-off completely. Radiation hardness testing of the AlGaN/GaN MOS transistors is performed using a 50 MeV ^{60}Co gamma source to explore effects of TID (total ion dose). Excellent I_{ds}-V_{gs} and I_{ds}-V_{ds} characteristics are measured even after exposures to a TID of 2Mrad. A slight decrease of saturation current (ΔI_{dss}~3 mA/mm) is observed due to the 2Mrad irradiation.

Keywords: AlGaN/GaN, MOS transistor, Schottky-free, high temperature, radiation-hard

1. INTRODUCTION

Harsh environments of extreme temperature, pressure, caustic, dusty, or strong radiation conditions, are one of the key operational requirements for advanced systems for aeronautical, automotive, nuclear, petrochemical, defense and space applications. *In situ* sensing, control, and monitoring in these harsh environments require robust high performance electronics as well as *in situ* sensors and detectors suitable for the extreme conditions.[1,2] In particular, high temperature electronics are necessary for petroleum well drilling (150-300 °C), hydrothermal system drilling (400-600 °C), automobile mechatronics (100-300 °C), aircraft electromechanical systems (up to 500 °C), and military battlefield weapon systems (-55 to 125 °C thermal cycling) [3]. High temperature electronics are also critical for future Venus (~480 °C) and Jupiter (~380 °C) *in situ* missions [2,4]. Strong radiation is a major challenge for satellite-based advanced systems and space missions, requiring radiation-hard electronics especially for future Europa (2 Mrad) orbiter and lander missions [2,4]. High pressure is another extreme condition to be coped with in various terrestrial and space applications as well, e.g., well logging (1700 bar) and atmospheric probe missions for Venus (92 bar) and Jupiter (22 bar) [2,4]. What makes it more challenging to develop technologies for harsh environments is that multiple extreme conditions often times coexist. Examples of such stipulations include a high temperature and pressure condition for well drilling, a high temperature and pressure and caustic condition for Venus *in situ* and mobile explorer missions and a low temperature (-160 °C) and high radiation condition for Europa explore mission [2,4].

To address these challenges, we develop GaN-based harsh environment electronics. III-nitride compound semiconductor materials have large band gaps (3.4 eV-6.1 eV) and strong atomic bonds (8.92 eV/atom for GaN and 11.52 eV/atom for AlN, compared to 2.34 eV/atom for Si) and they have excellent thermal and chemical stabilities and very favorable mechanical properties [5, 6]. Due to the wide bandgap, III-nitrides have minimal problems associated with unwanted optical or thermal generation of charge carriers. With these advantageous materials properties, GaN/$Al_xGa_{1-x}N$ devices offer a great potential for operations in wide temperature (-230°C to 500°C) [7-9] and pressure (0-5kbar) ranges [10-12],

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and in caustic or strong radiation environments, which cannot be achieved with conventional semiconductor device technologies currently available. It has been reported that GaN/$Al_xGa_{1-x}N$ heterostructure devices can reliably operate in 0-5000 bar range that the devices were tested with [10-12]. The goal of our current research is GaN electronics suitable for high temperature operation (500 °C) and strong radiation hardness (~ 2 Mrad).

While the need for high temperature (500 ºC) and radiation-hard (> 2 Mrad) electronics is eminent in the future space missions, currently no electronic devices/components with the required specifications are commercially-available. SiC-based transistors offer 500 ºC operations [13,14], but only with a compromise in the high speed performance. Current AlGaN/GaN transistors processed in a HEMT (high electron mobility transistor) layout using Schottky gates offer higher speed performances than SiC transistors. However, AlGaN/GaN HEMTs have not been reliably demonstrated for 500 ºC operations due to their gate burn-out, increased gate-leakage current, surface states, and degraded ohmic contact resistance at the elevated temperatures [15-17]. In terms of radiation hardness, it is reported that Ga atoms in GaN have displacement energy of ~19eV, similar to that of the atoms in SiC, but N atoms in GaN have no threshold energy of displacement damage due to their self-repairing processes. AlGaN/GaN HEMT devices have been reported to have radiation hardness of >2 Mrad at ~25°C [18, 19]. In our research, we explore AlGaN/GaN MOS (metal-oxide-semiconductor) transistors to overcome the drawbacks of the current GaN transistor technologies, by employing a Schottky-free MOS layout and refractory metallurgy. In this paper we present our recent study of AlGaN/GaN MOS HEMT with the focus on temperature dependence of electric characteristics and radiation hardness investigated with ^{60}Co radiation.

2. EXPERIMENTAL

The AlGaN/GaN MOS HEMTs are fabricated with $Al_{0.26}Ga_{0.74}N$/GaN heterostructures grown on Si(111) substrates, purchased from Nitronex Corp. The heterostructure consists of a GaN cap layer, a $Al_{0.26}Ga_{0.74}N$ layer, and a GaN buffer layer (figure 1a), where all the layers are undoped and grown by metalorganic chemical vapor deposition (MOCVD). For these structures, typical sheet charge density is ~$1x10^{13}/cm^2$ and electron mobility is ~ 980 cm^2/Vs. For device fabrication, mesa isolation of devices is carried out with chlorine-based ICP RIE (inductively coupled plasma reactive ion etching). Ohmic contacts for the source and drain electrodes are made with Ti/Al/Pt/Au layers by rapid thermal annealing at 850°C, and specific contact resistance of ~0.5-1 ohm-mm is obtained. Electron-beam evaporated Al_2O_3 is used as a gate dielectric. The gate electrode is fabricated with Pt using electron-beam evaporation. For high temperature testing and radiation-hardness study of the AlGaN/GaN MOS HEMTs, devices were packaged with Au thermo compression bonding for die attachment and Au-Au wire bonding between electrode contact pads of a device and pin pads of a device carrier (figure 1b,c) [20]. High temperature testing is carried out in a box furnace under N_2 environment, measuring electrical characteristics of the device at a room temperature and from 25C to 500C with a 50 degree increment. For radiation hardness study, AlGaN/GaN MOS HEMTs are tested to 2Mrad of TID (total ion dose) through exposure to ^{60}Co source. Exposure to radiation is performed in small increments up to 150Krad in the beginning. After 150Krad are accumulated, the data acquisition mode is placed on "auto-pilot" to monitor devices characteristics at every 50Krad measuring source-drain current (I_{ds}).

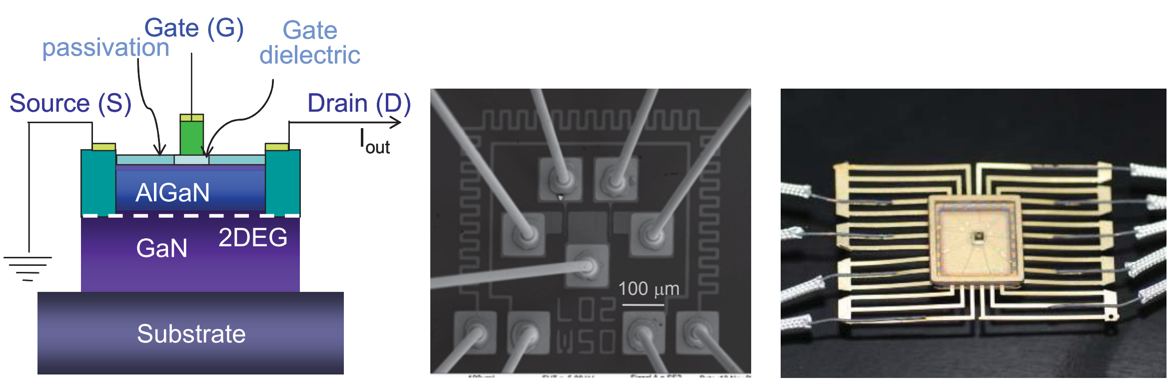

Figure 1 (a) Schematic of a cross sectional view of a AlGaN/GaN MOS HEMT (not drawn to scale) (b) SEM image of AlGaN/GaN MOS HEMT (c) photograph of AlGaN/GaN MOS HEMT packaged for high temperature testing

3. RESULTS AND DISCUSSION

3.1 Temperature dependence of electrical properties

For the temperature-dependent electrical characteristics study, AlGaN/GaN MOS HEMT fabricated with a gate length of 10 μm and a gate width of 50 μm (L10W50) is investigated. The I_{ds}-V_{ds} (source-drain current vs. source-drain voltage) curves and the transfer (I_{ds}-V_{gs}) curves of the AlGaN/GaN MOS HEMT measured at a room temperature and 200°C, 250°C, 300°C, 350 °C, 400 °C, 450 °C, and 500°C are shown in figures 2 & 3. At room temperature, the I-V curves show an excellent pinch-off behavior with the pinch-off voltage of -2.5 V (figure 2). The saturation current I_{dss} of 75 mA/mm is obtained with a low knee voltage of 2 V. Due to the relatively large gate length of 10 μm and source-drain separation of 14 μm, the on-state resistance (R_{on}) is 28 ohm-mm. The AlGaN/GaN MOSHEMT devices show excellent I-V curves up to 450 °C. The off-state degradation is not observed up to 400 °C and the good pinch-off characteristics are maintained with the pinch-off voltage of ~-2V. The I_{dss} is reduced to 20mA/mm at 400 °C. The off-state current started to increase at 450 °C. The I_{dss} is reduced to 14 mA/mm, and an increase in R_{on} is clearly observed with R_{on} of 85 ohm-mm at 450 °C. At 500 °C, the AlGaN/GaN MOSHEMT is not pinched-off completely and the off-state current is increased due to the gate leakage current. I_{ds}-V_{ds} and I_{ds}-V_{gs} investigated in the temperature range of 250°C- 500°C show a decrease of I_{ds} and an increase of R_{on} with increasing temperature. A slight increase of threshold voltage (i.e., less negative) is also observed at high temperatures. Further optimization of gate dielectric layer is currently underway to address the gate leakage current at the high temperatures.

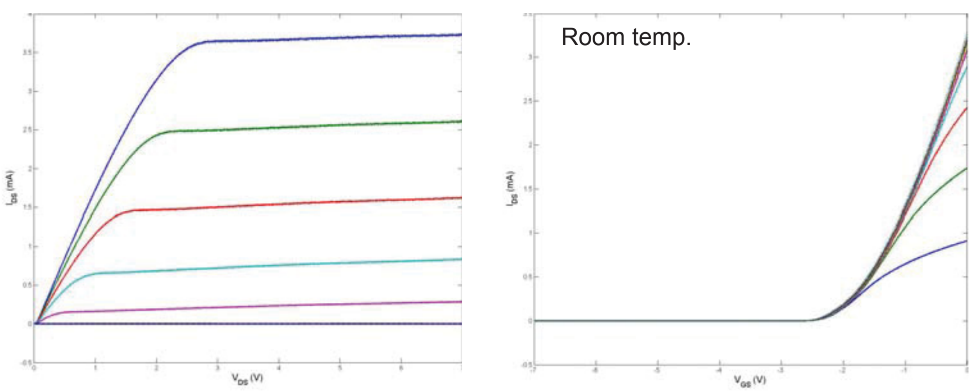

Figure 2. I-V curves of AlGaN/GaN MOS HEMT measured at a room temperature. (a) I_{ds}-V_{ds} curves measured in the source- drain voltage (V_{ds}) of 0-7 V at the gate voltage (V_{gs}) of -7.0 V to 0.0 with a 0.5V step. (b) I_{ds}-V_{gs} curves measured in the gate voltage (V_{gs}) of -7-0 V at the drain voltage (V_{ds}) of 0.5 V to 5.5V with a 0.5V step. The device is fabricated with a gate length of 10 μm, a gate width of 50 μm, and a source-drain distance of 14 μm.

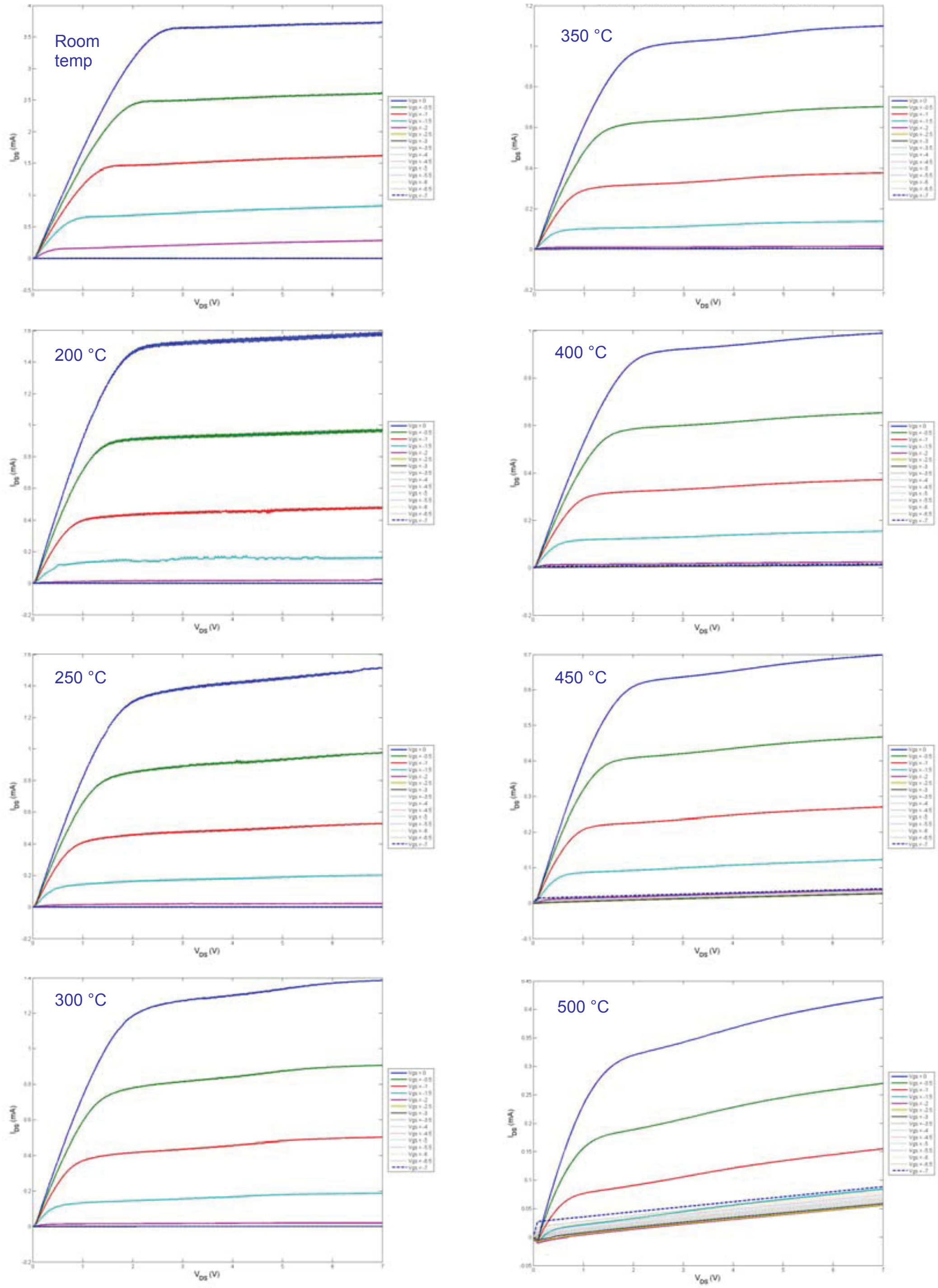

Figure 3. Temperature-dependence of I_{ds}-V_{ds} curves of AlGaN/GaN MOS HEMT measured from a room temperature to 500°C. The results presented are for a device fabricated with L=10 μm, W=50 μm, and DS=14 μm. I_{ds}-V_{ds} curves are measured in the source- drain voltage (V_{ds}) range of 0-7 V at the gate voltage (V_{gs}) of -7.0 V to 0.0 with a 0.5V step.

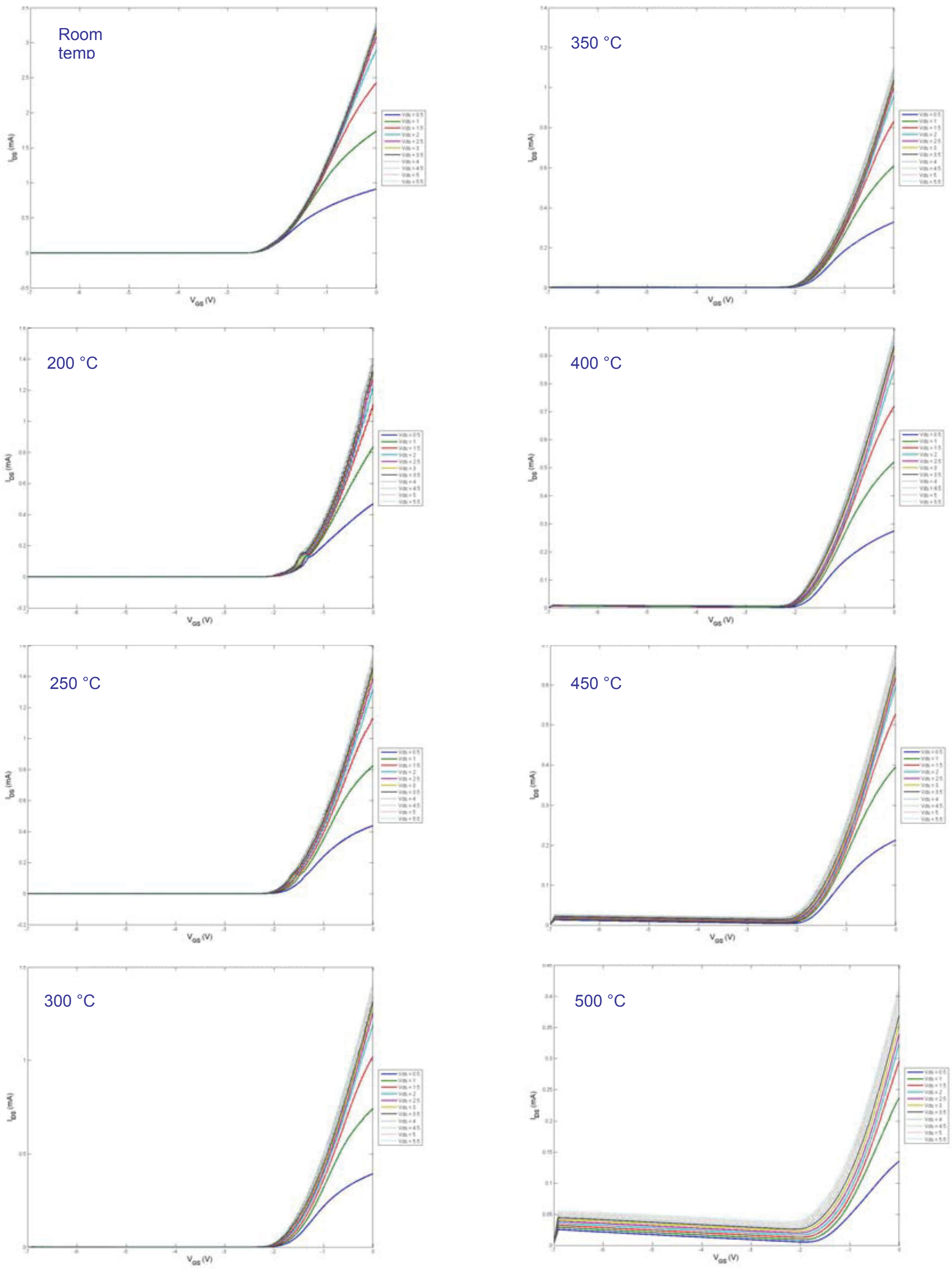

Figure 4. Temperature-dependence of I_{ds}-V_{gs} curves (transfer curves) of AlGaN/GaN MOS HEMT measured from a room temperature to 500°C. The data are acquired with a device fabricated with L=10 µm, W=50 µm, and DS=14 µm. I_{ds}-V_{gs} curves are measured in the gate voltage (V_{gs}) range of -7-0 V at the drain voltages (V_{ds}) of 0.5 V to 5.5V with a 0.5V step.

3.2 Radiation testing of electrical properties

The effects of TID (total ion dose) are studied with AlGaN/GaN MOS HEMT fabricated with a gate length of 6 μm and a gate width of 50 μm (L6W50). Figure 5 shows I_{ds}-V_{ds} and I_{ds}-V_{gs} curves taken before and after TIDs up to 150 Krad. The data are acquired first at TIDs of 5, 10, 20, 30, 50, 75, 100, and 150 Krad, considering that electronic devices are most sensitive to radiation during the initial doses. The results indicate a slight increase of saturation current I_{dss} (ΔI_{dss} ~3 mA/mm) due to a 150 Krad TID, but no significant change in threshold voltage (V_{th}) is observed. Excellent I-V characteristics with a low knee voltage (<2V) and a great pinch-off behavior remain after the 150 Krad TID. Figure 6 compares I_{ds}-V_{ds} and I_{ds}-V_{gs} curves taken after exposures to 150 Krad and 2 Mrad TIDs. The curves taken with the same operational parameters track each other very closely, indicating that no significant damage was caused by the additional TIDs reaching to 2 Mrad. Other AlGaN/GaN MOS HEMT devices fabricated with different gate lengths and gate widths show an increase in I_{dss} and a decrease (more negative) in V_{th}, with different degrees of changes depending on the gate electrode designs. However, for all the devices investigated, major changes have been observed during the initial TID of 150Krad.

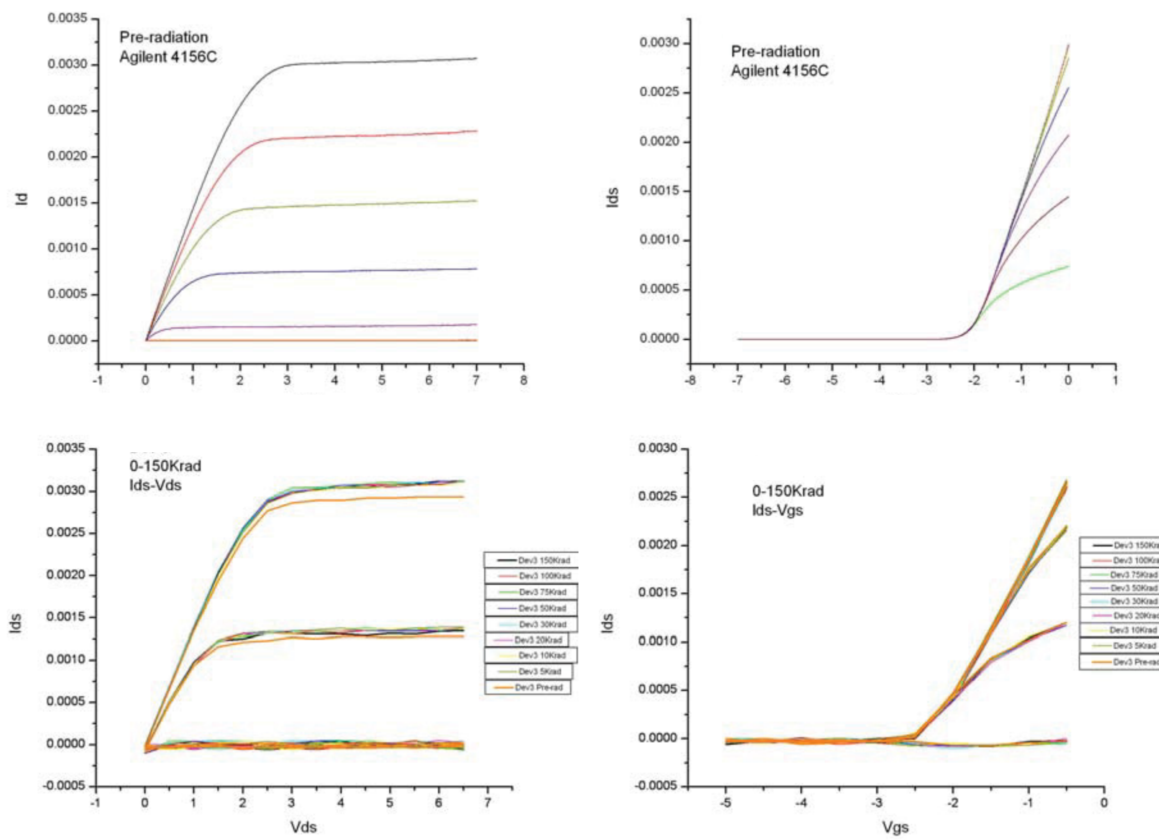

Figure 5. I_{ds}-V_{ds} and I_{ds}-V_{gs} curves of the AlGaN/GaN MOS HEMT (L=6 μm, W=50 μm, & DS=10 μm) measured before and after exposures to a ^{60}Co source. I-V measurements are conducted with accumulated doses of 5, 10, 20, 30, 50, 75, 100, & 150 Krad. Pre-radiation I_{ds}-V_{ds} curves are measured in a source- drain voltage (V_{ds}) range of 0-7 V at the gate voltages (V_{gs}) of -7.0 V to 0.0 with a 0.5V step. Pre-radiation I_{ds}-V_{gs} curves are measured in a gate voltage (V_{gs}) range of -7-0 V at the source-drain voltages (V_{ds}) of 0.5 V to 5.5 with a 0.5V step. For after-radiation characterization, 1.0 V steps of V_{gs} and V_{ds} are used for I_{ds}-V_{ds} and I_{ds}-V_{gs} measurements.

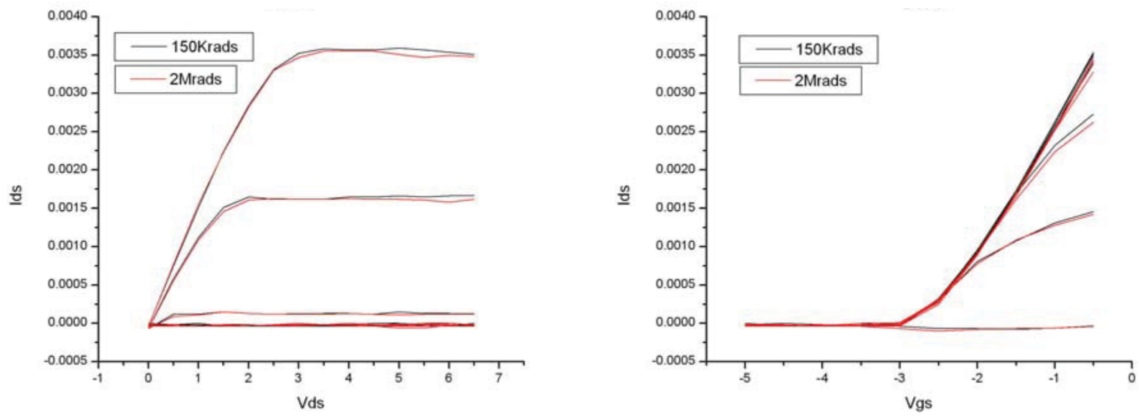

Figure 6. I_{ds}-V_{ds} and I_{ds}-V_{gs} curves of the AlGaN/GaN MOS HEMT (L=6 μm, W=50 μm, & DS=10 μm) measured after 150Krads and 2 Mrads exposures to a ^{60}Co source. I_{ds}-V_{ds} curves are measured in a V_{ds} range of 0-7 V at the gate voltage (V_{gs}) of -7.0 V to 0.0 with a 1.0V step. I_{ds}-V_{gs} curves are measured in a V_{gs} range of -7-0 V at the source-drain voltage (V_{ds}) of 0.5 V to 5.5 in 1.0V steps.

4. SUMMARY

Schottky-free AlGaN/GaN MOS HEMTs, where a gate electrode is fabricated in a MOS layout with Al_2O_3 gate dielectric, are studied for high temperature operation and radiation hardness. The I_{ds}-V_{gs} and I_{ds}-V_{ds} curves measured in the temperature range of 25°C- 500°C show an excellent pinch-off behavior up to 450°C. Off-state degradation becomes measurable at 450 °C. The off-state current is increased at 500 °C, and the AlGaN/GaN MOS HEMT does not get pinched-off completely. Improvement of the gate dielectric and its interface to the AlGaN/GaN layers is in progress to address the gate leakage current at at 500 °C. The TID radiation testing performed using a 50 MeV ^{60}Co gamma source shows excellent I_{ds}-V_{gs} and I_{ds}-V_{ds} characteristics even after exposures to a TID of 2Mrad. The results indicate that the AlGaN/GaN MOS HEMTs are quite promising for operations at high temperatures and/or in strong radiation conditions.

5. ACKNOWLEDGEMENT

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